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**Report No. A-11**

**FINAL REPORT (NASW-2144)**

Report No. A-11

FINAL REPORT (NASW-2144)

by

Astro Sciences

of

IIT Research Institute  
Chicago, Illinois

for

Planetary Programs  
Office of Space Science  
NASA Headquarters  
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APPROVED:



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## FOREWORD

This final report summarizes the reports prepared and the special tasks performed by Astro Sciences of IIT Research Institute during the period from November 1971, through January 1973. Seven reports and technical memoranda are summarized together with a listing of five advanced planning tasks on which no formal reports have been written. A brief description of support work for North American Rockwell's SEP Stage Study is also contained within this report. This work has been performed under NASA Contract Number NASW-2144.

IIT RESEARCH INSTITUTE

# NINTH ANNUAL SUMMARY REPORT

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FINAL REPORT (NASW-2144)

LONG RANGE PLANNING FOR SOLAR SYSTEM EXPLORATION

NOVEMBER, 1971 - JANUARY, 1973

1. INTRODUCTION

Astro Sciences of IIT Research Institute (AS/IITRI) has been engaged in a program of advanced research, study and analysis for the Planetary Programs Division (Code SL) of NASA since March, 1963. The results of Astro Sciences' work up to October 31, 1971, have been previously reported<sup>1</sup>. This report summarizes the work performed on Contract NASW-2144 from November 1, 1971 through January, 1973.

The purpose of advanced mission planning is to derive a preliminary understanding of those missions, and associated mission requirements, which are of importance in the evolution of knowledge of our solar system. It is necessary not only to have a solid foundation in science and engineering for this type of planning but also the ability to integrate the increasing awareness of the problems involved in space exploration back into the advanced planning process. Astro Sciences' program during the period covered by this report, as it has during the previous eight years, has continued to develop this process in accordance with NASA's broadening needs.

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<sup>1</sup> The contract work conducted between March 1, 1963 and December 1, 1968 is summarized in AS/IITRI Report No. A-6, "Long Range Planning Studies for Solar System Exploration" (1969). Work done between December 1, 1968 and October 31, 1969 is summarized in AS/IITRI Report No. A-7, "Long Range Planning for Solar System Exploration" (1970). Work done between November 1969 and October 1970 is summarized in AS/IITRI Report No. A-9, "FINAL REPORT" (NASW-2023) (1970), and work done between November 1970 and October 1971 in AS/IITRI Report No. A-10, "FINAL REPORT" (NASW-2114) (1971).



The activities of Astro Sciences are reported to the Planetary Programs Office at regularly scheduled bi-monthly review meetings. However, the most tangible output is in the form of technical reports and memoranda. During the time period covered by this report a total of seven reports or technical memoranda have been submitted. Summaries of these documents are given in Section 2. Section 3, Special Studies and Activities, summarizes study efforts that have been performed but for which no formal reports have been published. Section 4 contains a bibliography of reports and technical memoranda published by AS/IITRI. Finally, Section 5 summarizes the major computer programs used to support Astro Sciences' technical efforts.

**2. SUMMARY OF REPORTS AND TECHNICAL MEMORANDA  
PUBLISHED NOVEMBER 1971 - JANUARY 1973**

## 2.1 MISSION OBJECTIVES

Technical Memorandum No. P-42  
"ASTEROID SELECTION FOR MISSION OPPORTUNITIES"  
by C. Chapman and C. Stone  
November, 1972

Missions to the asteroid belt and to specific asteroids were identified as scientifically important very early in the space program and flyby opportunities to one or more of the larger asteroids have appeared in NASA long range plans for a number of years. These opportunities have largely been selected on the basis of launch opportunity and mission energy requirements. More recently it has become apparent through rapid advances in our limited knowledge of the asteroids that the major questions which relate to solar system minor bodies will not be satisfactorily answered, even in the first order, by a mission or missions to a single asteroid. Concurrently, advanced propulsion systems are being developed or planned which expand the mission possibilities for minor bodies. Solar electric propulsion (SEP) and nuclear electric systems (NEP), when available, are capable of performing rendezvous and orbit, multiple asteroid flybys, and lander missions.

This preliminary study was undertaken to assess the present state of knowledge of asteroids as well as the rate of change of that knowledge to better identify the mission and target priorities for the advanced planning of asteroidal flights in the 1980's and beyond. It was apparent at the outset that there was not a unique set of asteroids representing maximum priority. Equally important, ground based observations and studies will undoubtedly alter priorities assigned to specific asteroids as our knowledge increases. Thus this report presents a review of current knowledge and derives a categorical set of priorities which can be applied to asteroid selection or evaluation by the reader. A preliminary selection has been made

both to illustrate the process and to provide the basis for early mission analysis but this selection should not be construed as representing the only choice nor even the "best" one.

The report discusses the present state of asteroid knowledge, the scientific goals and priorities attached to asteroid exploration, the anticipated advances in knowledge over the current decade, asteroid mission consideration and, finally, asteroid selection. To summarize, in selecting priority targets the highest weight should be given to characteristics of spectral reflectivity variations with rotation. High weight should be given to albedo, especially extreme values. Medium weight should be given to albedo variations with rotation, large light-curve amplitudes, and family membership. Low weight should be given to extreme (especially rapid) rotations. Little or no weight should be given to other parameters.

It is most important to observe the asteroids with these important compositional characteristics as a function of semi-major axis (highest priority), diameter (high priority), and proper  $e$  and proper  $i$  (especially as related to probably extreme values of  $a$  in the early solar system, or large distances above the ecliptic). Therefore we want a variety of asteroids which span important ranges of both distance from the sun and diameter which hopefully also have a variety of implied compositions and many of which have evidence for having exposed their interiors as a result of catastrophic collisions. Asteroids should be observed over at least the range of 40 to 350 km diameter. It is important also to span the asteroid belt; the sample should include an asteroid inside of  $a = 2.4$  and an asteroid with aphelion distance beyond 3.5 AU.

Thus, from the point of view of current knowledge about the asteroids, we believe that the major emphasis should be to get close to as many asteroids as possible, constrained by two criteria: 1) At least one major asteroid should be visited, the surface characteristics of which suggests possible differentiation; 2) A reasonably wide range of semi-major axes should be explored, particularly including at least one asteroid (preferably of bluish color) in an orbit reaching aphelion beyond 3.5 AU. Even these criteria should not be regarded as strict. One would probably not wish to give up the opportunity to visit six different asteroids on the same mission if meeting the above criteria reduced the number of targets to only two or three.

Table 1 and Table 2 illustrate the comparative ratings developed from this study. The characteristics of asteroids were assigned relative ratings based on the current level of knowledge and the known data. The values of individual parameters were then assigned a secondary interest rating. The data for the 118 asteroids were then used together with the rating system to classify the asteroids. The groupings of higher interest asteroids which results is shown in Table 1. The system was used to rate several three asteroid missions as an example. The process is outlined in Table 2.

A compilation of all reliably known physical data about the asteroids is contained in the appendix (separately bound). There is a data sheet for each of 118 asteroids for which information, in addition to orbital parameters and magnitude, is available. Data that is considered unreliable (primarily old data such as results of photographic photometry) have been omitted. The information is up to date as of June, 1972 and includes the following parameters: the absolute B magnitude; B-V and U-B colors observed as a function of phase angle, also

1	2	3	4
4, 5, 15, 17 39, 1437	2, 3, 6, 7, 18, 19 25, 40, 192, 321 324, 433, 532, 624 1566	1, 9, 10, 12, 14, 16 20, 21, 22, 23, 28, 29 43, 44, 45, 51, 60, 61 68, 79, 82, 116, 186 196, 345, 349, 354 364, 409, 511, 563 911, 984, 1620	8, 11, 13, 24, 27, 30 37, 38, 42, 54, 62, 70 77, 78, 80, 85, 89, 92 93, 110, 162, 230, 258 268, 337, 341, 356 380, 481, 510, 540 554, 658, 674, 704 753, 779, 1287, 1291

TABLE 1. RELATIVE INTEREST GROUPING BASED ON SURFACE & COMPOSITIONAL CHARACTERISTICS.

Mission (Asteroid No.'s)	68 - 1 - 1293	67 - 1 - 544	540 - 116 - 223	1156 - 116 - 223
Compositional Interest Rating	3 3 --	-- 3 --	4 3 --	-- 3 --
Size (Magnitude)	160 290 --	290 --	-- (8.8 D<100) --	-- (8.8 D<100) --
a	2.78 2.76 2.23	2.42 2.76 3.17	2.22 2.77 3.09	2.26 2.77 3.09
e	.142 .101 .271	.187 .101 .195	.138 .174 .121	.043 .174 .121
i	7.5 9.7 5.4	6.0 9.7 11.2	6.1 3.6 1.97	1.43 3.6 1.97
Mission Scientific Rating (Relative)	1	2	3	4

TABLE 2. RELATIVE RATING OF MULTIPLE MISSIONS

as reduced to 5° phase using lunar phase corrections; a description of asteroid color derived from reliable measurements of all kinds; several descriptions of the spectral reflectivity curve; phase factors for UBV magnitudes and colors; characteristics of the polarization versus phase curve; light-curve characteristics, including period, minimum and maximum amplitude, relative proportion of variability due to albedo differences and shape, and implied axis orientation; mass; diameter; albedo, proper orbital elements; and family membership. The appendix identifies the asteroids by name and by their assigned number. For convenience, subsequent tables in the body of the report identify the asteroids by number only.



Report No. P-43

"INSTRUMENT TECHNOLOGY FOR MISSIONS TO ASTEROIDS AND COMETS"

by R. Sullivan and D. Klopp

January, 1973

Missions to asteroids and comets have an important and planned role in the exploration of the solar system. Present spacecraft and propulsion systems are adequate for some preliminary missions and the advent of SEP/NEP capabilities will permit a variety of minor body flyby and rendezvous missions in the 1980's. The scientific objectives associated with minor body exploration are similar to those for planetary exploration; however, some specific differences in objectives do exist. These differences together with the size of these bodies and the characteristic miss distances projected have generated questions about the adequacy of scientific instruments for these missions.

This study derived measurement specifications for the scientific objectives which have been established for flyby and rendezvous missions to comets and asteroids. These measurement specifications were then combined with typical spacecraft target separations and target size to estimate instrument requirements such as sensitivity, resolution, response time, spectral range, etc. Table 3 lists the spacecraft/target separations which were used. These were based on ephemeris errors and projected S/C capabilities but were chosen conservatively to place maximum demand upon the scientific instruments. The instrument requirements were then compared with the

Table 3: Typical Encounter Speeds and Probable Miss Distances

<u>Flybys:</u>		Encounter Speed	Probable Miss Distance
Asteroids		5 - 12 km s <sup>-1</sup>	~ 100 km
Comets		~ 12 km s <sup>-1</sup>	~ 1000 km
<u>Rendezvous:</u>		Encounter Speed	Probable Miss Distance
Asteroids		0	10 km (orbit?)
Comets		0	10 km

characteristics of presently available flight rated hardware. When the requirements for minor body exploration exceeded those presently available, expert opinion was obtained on the nature of the R & D required. Based on these inputs the instruments were classified in one of three categories:

1. Adequate flight instruments exist which require only engineering and integration.
2. The basic technology for the instrumentation is available and the normal 3-5 year R & D cycle following mission approval should provide flight hardware.
3. The requirements are sufficiently stringent to warrant R & D expenditures in advance of mission approval to ensure the availability of adequate flight instrumentation.

The judgements involved in the classification were, of course, subjective and it was occasionally difficult to establish a firm "minimum" capability against which to make decisions. Obviously, increases in sensitivity, resolution, etc. will yield better data and the scientific community will always desire continued instrument development. However, based on what we feel are reasonable objectives, the available instruments satisfy most projected needs. Table 4 summarizes the results. Mass spectrometers for comet missions are a borderline case. An increase in efficiency is necessary and it is not clear that the normal mission hardware cycle time is adequate. High resolution gamma ray spectroscopy will require further development of intrinsic Ge detectors but research in this area is underway with DOD and AEC support. No instrumentation exists which will simultaneously measure the mass, diameter and velocity of meteorites and dust particles but this

Table 4: Development Requirements for Minor Body Science Instruments

Instrument	1. Adequate Flight Instrumentation Exists	2. Technology Available for Mission Cycle R & D	3. Advanced R & D Required
Meteoroid Radar		1. x	
Microwave Radiometer	x		
IR Radiometer	2. x		
IR-V-UV Spectrometer		3. x	
V-Imagers		x	
V-UV Photometer	x		
X-Ray Spectrometer		x	
γ-Ray Spectrometer			4. x
Mass Spectrometer		5. x	
Magnetometer	x		
Plasma Probe	x		
Plasma Wave Experiment		x	
Micrometeroid Detector			6. x
Gravity Gradiometer		x	

1. While sensitivities are satisfactory, weight and power requirements are high compared to scientific value.
2. Spatial resolution for comet nuclei of 1 km diameter is 1/10 of a diameter.
3. Based on slit spectrometer which, however, does not provide two dimensional spatial resolution.
4. This assumes that high resolution spectroscopy will be required.
5. Estimates of the effort required to achieve desired throughput vary. Advanced R & D might be required.
6. Flight hardware does exist but does not provide desired information. Cometary dust is the pacing scientific objective.

is a long standing problem. The weight and power limitations for these missions are similar to those for planetary exploration and obviously some of the scientific instruments would benefit from further advances in miniaturization.



## 2.2 MISSION ANALYSIS

Technical Memorandum No. M-36  
"SATURN ORBITER MISSION STUDY"  
by W. Wells and R. Sullivan  
January, 1973

This report provides a preliminary analysis of the important aspects of missions orbiting the planet Saturn. Orbital missions to the outer planets can be given serious consideration in the 1980's or after flybys by Pioneer 10/G and Mariner Jupiter-Saturn '77. Previous studies (by IITRI/Astro Sciences, JPL and NASA/Ames) have looked at Jupiter orbiters. This effort attempts to characterize Saturn orbiters in similar detail so that comparisons with Jupiter missions can be made.

Broadly speaking, the scientific objectives of Saturn exploration can be grouped under four topics: 1) the atmosphere, 2) the magnetosphere, 3) the rings and 4) satellites. Like Jupiter, Saturn has an atmosphere consisting of belts and zones whose global circulation pattern and local features can be studied by long term monitoring (imagery) from an orbiting spacecraft. The vertical profiles of temperature, pressure, etc. can be deduced from spectroscopic and occultation measurements. Saturn's magnetic field and radiation belts, for which only upper limits can be given, could be very similar to Jupiter's and can be investigated using standard fields and particles measurement techniques. The rings are the truly unique feature of the Saturn system and the primary objective is to describe their photometric properties from which the sizes, shapes and composition of particles can be inferred. Saturn has ten satellites including Titan, the largest, which has an atmosphere; Iapetus, known for its large amplitude light curve, and Janus which is so small and close to the rings that it has been seen only four times. Imagery is the most useful technique for studying the satellites.

A suggested visual imaging instrument has been designed around the standard Mariner vidicon. Two identical 30 cm focal length lenses are used, similar to the arrangement for MVM '73. Saturn fills the field of view at a range of  $60 R_s$ , a typical apoapse distance, where the surface resolution is 330 km per line pair. However, if the spacecraft is spin stabilized, a multi-detector spin scan camera should be used. Its resolution at the same distance is 700 km per line pair. The weight of each candidate instrument and an example of a similar one are given in Table 5.

For accurate photometric measurements a separate photopolarimeter with five or more spectral bands is needed. It and the selected infrared (IR) radiometer have a  $0.5^\circ$  field of view or a resolution of 3000 km at  $6 R_s$ . The radiometer has a signal to noise ratio of at least 100 in two bands, 20-35 $\mu$ m and 60-100 $\mu$ m. Radio occultation and radio tracking data are derived from an analysis of the dual frequency radio signal received at the earth. A microwave radiometer channel at 13 cm can and should be added to the spacecraft command receiver.

An ultraviolet (UV) spectrometer, which has fixed detectors for measuring specific emission and absorption lines of H, H<sub>2</sub>, He and other less abundant species, is easily constructed with 20 Å spectral resolution. A  $1/3 \times 3^\circ$  field of view is appropriate even though an atmospheric scale height is not resolved during airglow measurements of Saturn's limb. It is very difficult to get both good spectral and spatial resolution in the IR, even with an interferometer. The best option is to measure absorbed solar radiation between about 1 and 5 $\mu$ m. The magnetosphere, its interaction with the solar wind and its trapped particles are measured with a complementary set of instruments including a magnetometer, charged particle detectors and radio receivers to record plasma waves and planetary emissions.



Table 5  
INSTRUMENTS FOR SATURN ORBITERS

Instrument	Weight	Payload		Similar Instruments
		#1	#2	
TV System	30	x	-	Mariner 9
Spin Scan	12	-	x	ATS
Photopolarimeter	4	x	x	Pioneer 10
IR Radiometer	4	x	x	Pioneer 10
Radio Science	-	x	x	Viking
UV Spectrometer	4	x	a	Mariner '73
IR Spectrometer	15	x	-	Mariner 9
Magnetometer	3	x	x	Pioneer 10
Charged Particles	5	a	x	Pioneer 10
Plasma Wave	4	a	x	OGO
Radio Astronomy	3	a	x	RAE
Micrometeoroid Detector	5	a	x	Helios
Total Payload #1	60			
Payload #2	36			

x = selected

a = alternate

Finally, there is a micrometeroid composition detector which determines the mass of ions formed by hypervelocity impacts.

Two payloads have been selected from these candidate instruments. The first emphasizes atmospheric measurements and is intended for a Mariner spacecraft which has inertial stabilization and a science payload capacity of 60 kg. The fields and particles instruments are well represented in the second payload which is made up of experiments which can work well on the spin stabilized Pioneer spacecraft. The pointing requirements of the TV system and IR spectrometer prevent them from being alternate instruments for the Pioneer payload. Their weight is also a problem.

The rings of Saturn are a hazard to an orbiting spacecraft which crosses the equatorial plane at a radius of less than  $2.3 R_s$ . Because of uncertainties about the full spatial extent of the rings a nodal radius of  $3.0 R_s$  was selected for nominal missions and  $4.0 R_s$  for a worst case analysis. Microwave observations of Saturn have not established the presence of radiation belts, but the upper limits are consistent with the nominal model for Jupiter's trapped particles. A spacecraft with a periapse of  $3.0 R_s$  or more can survive for at least ten orbits in the nominal environment. Because the rings cut off the belts at  $2.3 R_s$ , a periapse of  $1.6 R_s$  can also be used. For a worst case analysis a periapse of four Saturn radii is appropriate.

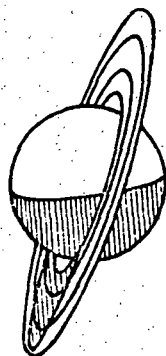
There are three types of orbits that are useful for Saturn orbiter missions. The first maximizes the phase angle coverage for atmospheric and ring system measurements by using an orbit plane that passes very near the subsolar point. Figure 1a shows that the spacecraft's motion, as typically seen from the sun, passes in front of the rings and Saturn's disc so that  $0^\circ$  phase angle data is obtained over the full radial extent of the rings.

# MAXIMUM PHASE ANGLE ORBIT

ATMOSPHERIC OCCULTATION

EXTINCTION

BACKSCATTER



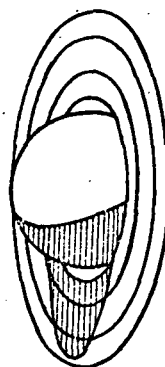
(c) VIEW OF SATURN FROM APOAPSE

(a) VIEW OF ORBIT FROM SUN

# MINIMUM PERIAPSE RADIUS ORBIT

ATMOSPHERIC OCCULTATION

EXTINCTION



(d) VIEW OF SATURN FROM APOAPSE

(b) VIEW OF ORBIT FROM SUN

FIGURE 1. VIEWING CONDITIONS FOR CANDIDATE ORBITS

Then the spacecraft passes behind the rings and both solar extinction and radio occultation measurements can be made. Such an orbit should have a periapse radius of  $3.0 R_s$  and a period of 15 to 30 days. During the long periods of time near apoapse the spacecraft is well positioned to observe the global atmospheric circulation pattern (see Figure 1b). Close passes of Titan, the largest satellite, can often be arranged in conjunction with this orbit.

Taking the periapse as  $1.6 R_s$  minimizes the energy requirement for orbit capture. But the orbit plane is then restricted so that the node is at  $3.0 R_s$ . Typically this type of orbit does not have complete phase angle coverage. The view from the sun in Figure 1c shows that no  $0^\circ$  coverage is acquired. From apoapse the view is about the same as the previous case. A particular advantage of this orbit is the fact that it penetrates the magnetic field to the  $2.15 R_s$  shell and can observe the effects of the rings on the trapped particles. Close encounters with the larger satellites are not possible.

Finally for maximizing the number of close encounters with satellites, an elliptical orbit is essential. This requires two additional impulses to first change the plane and then reduce the orbit period to about 16 days which is an integer multiple of the period of five satellites. The equatorial orbit also has a view of the atmosphere unobstructed by the rings but with the polar regions always forshortened.

The first payload option could be used on each of the three candidate orbits although it might be profitable to include the fields and particles instruments on the minimum periapse radius orbit. The net mass (excluding propulsion) of a Mariner spacecraft which can provide data storage for  $5 \times 10^8$  bits, data transmission at 45 Kbps and  $\pm 0.8$  mrad pointing for these instruments is estimated to be 608 kg. Most subsystems would be

very similar to the MJS '77 ones. The larger propulsion system would require structural changes similar to the difference between 1969 Mars flyby and the 1971 orbiter. A proposed MJS '77 revision of the radio system was assumed which would improve its scientific capabilities and decrease its weight.

The second payload option belongs on a Pioneer spacecraft in the minimum periapse or maximum phase angle coverage orbit. Significant changes to the current Pioneer 10/G spacecraft are required to convert it to a Saturn orbiter. A maximum data rate of 12 Kbps is provided by a new 10 w X-band transmitter and storage is increased to  $3 \times 10^5$  bits. Two MHW RTG's are employed to achieve 230 w of spacecraft power at end of mission. Structural changes caused by the larger power source and orbit capture propulsion system bring the net mass in orbit to an estimated 312 kg (excluding propulsion).

The optimum year for direct ballistic trajectories to Saturn is 1985. Launch vehicle performance for this opportunity and the spacecraft requirement are both plotted in Figure 2 as approach mass versus approach speed. The flight time can be determined from the intersection of one curve with another. A Pioneer spacecraft can be placed into orbit after a four year flight and a Titan III E Centaur/TE-364 launch. The more powerful Shuttle/Centaur/HE BII reduces the flight time to 3.3 years.

The Shuttle/Centaur/HE BII is just able to put a Mariner spacecraft into this orbit. For a flight time of 4.2 years, the minimum periapse radius orbit can be achieved. Actually it will be difficult to state the Shuttle performance until its operating requirements, such as launch window and the availability of a larger chemical or nuclear state (neither of which is well defined) are determined. Solar electric propulsion, however, is capable of putting the nominal Mariner spacecraft into the  $3.0 R_s$  periapse orbit. Using the Shuttle/Centaur/SEP (20 kw)

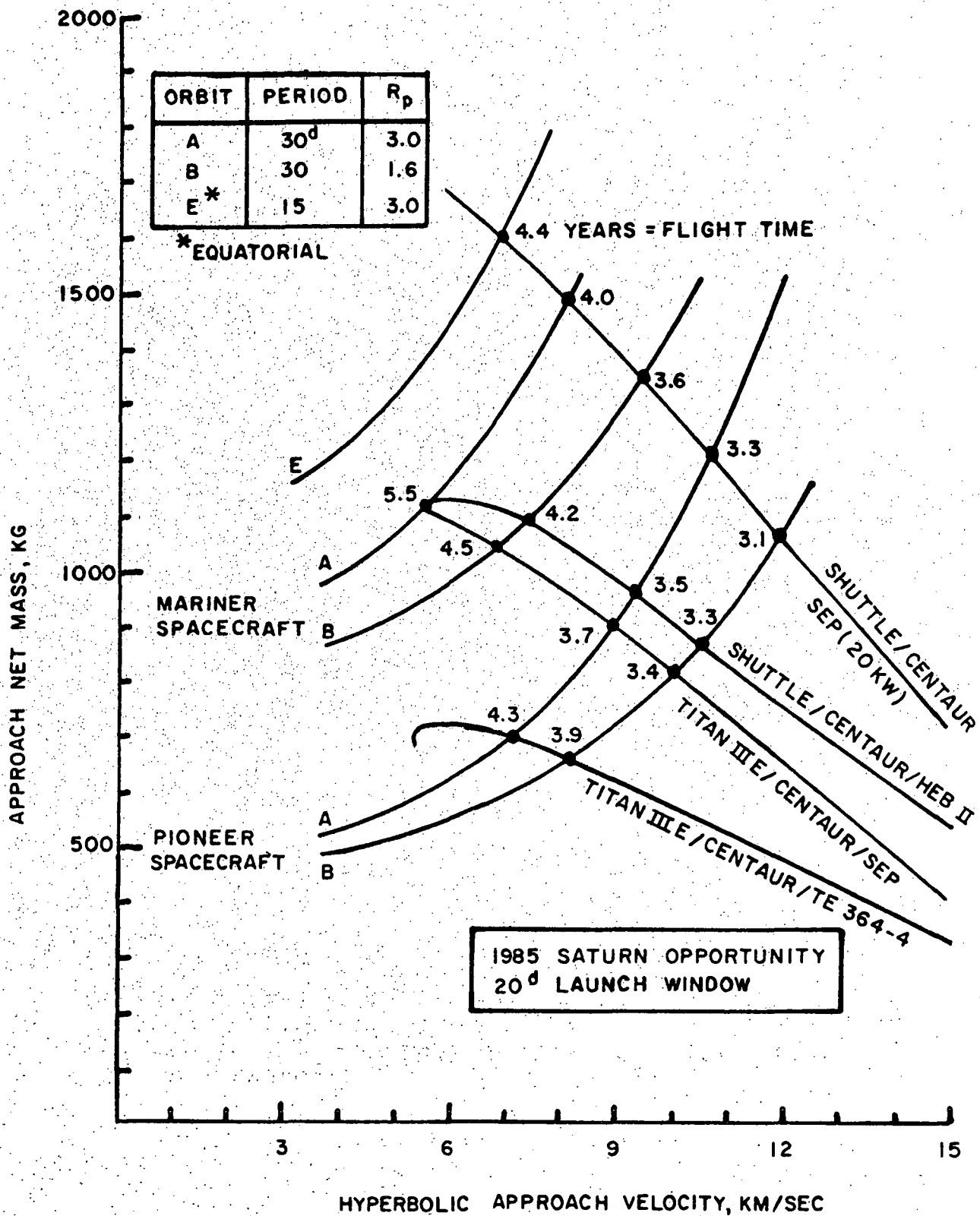


FIGURE 2. SPACECRAFT REQUIREMENTS AND LAUNCH VEHICLE PERFORMANCE.

vehicle and allowing a total of 900 kg for the SEP stage which is jettisoned before orbit capture, the flight time is 4.0 years. Even for an equatorial orbit the flight time is 4.4 years. The flight times are independent of launch opportunity.

The obvious differences between Saturn and Jupiter orbiter missions are: 1) a five year mission rather than three years, 2) a typical communications distance of 10 AU rather than 5 AU which makes the data rates differ by a factor of 4, and 3) a significantly larger launch vehicle. The longer lifetime requirement is less significant for the Mariner spacecraft while the Pioneer needs improvements in several key subsystems to qualify as a Saturn orbiter. These changes would also be beneficial for a Pioneer Jupiter orbiter.

Most of the instruments which have been selected for the Saturn orbiter payloads could also be used at Jupiter. The data rate difference will affect the operation of the imagery system and perhaps the design of its optics. The higher infrared flux from Jupiter means it would be easier to design an IR spectrometer for use only in Jupiter orbit. The micro-meteoroid detector could be dropped from consideration at Jupiter.

Attempts to improve our knowledge of Saturn's rings, magnetic field and radiation belts prior to the MJS '77 flyby are recommended as a method of permitting earlier final design work for an orbiting spacecraft. Assuming that the Shuttle upper stage and its operating characteristics will permit it, the Mariner spacecraft is more attractive. It would make sense to use two spacecraft so that all the candidate instruments can be utilized. The first would have payload #1 and go into the  $3.0 R_s$  periaipse orbit which encounters Titan. On the second spacecraft room would be made for fields and particles instruments by dropping some instruments from payload #1, such as the IR spectrometer. This spacecraft should be placed in the minimum periaipse orbit.





## 2.3 TRAJECTORY STUDIES

Report No. T-31  
"ADVANCED MISSION APPLICATIONS OF NUCLEAR ELECTRIC  
PROPULSION"  
by D. Spadoni  
July, 1972

Current analysis of advanced unmanned planetary missions in the 1980's and beyond indicate the need for propulsion systems with performance capabilities beyond those of current and near state-of-art. One propulsion system concept being considered to fill this need is nuclear electric low thrust propulsion (NEP). The only on-going NEP development program is the internally-fueled thermionic reactor. The major development effort is concentrated on design proof and testing of the thermionic fuel element and overall reactor design. Technology forecasts indicate that an internally-fueled thermionic NEP system capable of 20,000 hour operating thrust time could be available for mission application by late 1983.

Two different NEP system power levels are considered for performance analysis: 100 kw and 250 kw. The 100 kw NEP system uses a Centaur (D-1T) chemical stage for injection to an inter-planetary transfer and the 250 kw system uses a spiral escape maneuver. Advanced chemical systems used for ballistic performance comparison are the Centaur (GT)/Kick, Centaur (GT)/VUS and Centaur (GT)/Centaur (GT)/VUS. All systems are launched to a 270 n.mi. parking orbit via the space shuttle with a payload capability of 50000 lbs.

The set of missions selected for performance analysis includes loose elliptical orbiters and close circular orbiters of the outer planets, satellite orbiter/landers, a Saturn-Uranus-Neptune flyby, Halley rendezvous, and Ceres sample return. Performance comparison is in general made on the basis of net payload at the target as a function of flight time. NEP performance is shown for unconstrained and constrained (20,000 hours) thrusting time. Specific impulse is optimized and ranges from 4000 sec to 7000 sec.

In general, results show that both NEP systems are capable of performing all the missions considered but that the ballistic systems could perform only those missions requiring a moderate expenditure of energy at the target (loose elliptical orbiters, satellite orbiter/landers, and multi-planet flyby). For these missions, the NEP systems are found to yield as high as 30% (100 kw) to 50% (250 kw) reduction in flight time for a given payload over the chemical ballistic systems. Table 6 shows for a selected net payload, flight time results for the various missions considered. The NEP data are for systems constrained to a maximum operating thrust time of 20000 hours. For the payload levels indicated, the 250 kw system out-performs the 100 kw system only in those missions requiring relatively high energy expenditure. For moderate energy levels, the two systems are comparable.

A detailed analysis of the Ceres sample return mission showed that the 100 kw NEP system has the capability to return as much as 120 kgs of surface sample plus a photographic coverage at 1 meter resolution of 100% of the asteroids' surface.

TABLE 6 PROPULSION SYSTEM-FLIGHT TIME COMPARISONS

TARGET	MISSION TYPE	NET PAYLOAD (KGS)	NEP (100) <sup>3</sup>	FLIGHT TIME (DAYS) <sup>2</sup> NEP (250) <sup>3</sup>	CHEMICAL
JUPITER	30-DAY ORBITER	1000	450	500	545
	SYNCHRONOUS ORBITER	1000	1520	1350	-
CALLISTO	ORBITER/LANDER	1740 <sup>1</sup>	910	870	1000
	ORBITER/LANDER	1830 <sup>1</sup>	1460	1145	-
SATURN	30-DAY ORBITER	1000	940	950	1130
	RING ORBITER	1000	1640	1570	-
TITAN	ORBITER/LANDER	1890 <sup>1</sup>	1660	1400	1660
	30-DAY ORBITER	1000	1850	1725	2440
URANUS	SYNCHRONOUS ORBITER	1000	2600	2460	-
	30-DAY ORBITER	1000	2850	2630	4075
NEPTUNE	SYNCHRONOUS ORBITER	1000	4140	-	-
	MULTI-PLANET FLYBY	1000	< 2400	NA	2640
HALLEY	RENDEZVOUS	1000	950	950	-
CERES	SAMPLE RETURN	NA	1250	NA	-

1. MINIMUM REQUIRED PAYLOAD IN SATELLITE ORBIT RECOMMENDED BY PRICE AND SPADONI (1970).
2. - INDICATES SYSTEM NOT CAPABLE OF PERFORMING MISSION.  
NA INDICATES SYSTEM NOT APPLIED TO MISSION.
3. RESULTS SHOWN ARE FOR CONSTRAINED THRUST TIME (20000 HR MAXIMUM).



Technical Memorandum No. T-32  
"PLANETARY MISSIONS HANDBOOK (FIRST EDITION)"  
July, 1972

The Planetary Missions Handbook provides a consistent source of payload performance data for missions to the outer planets. The payload data for both flybys and orbiters is presented graphically as a function of flight time for various launch years, launch vehicles, and orbit sizes. All the relevant parameters have been combined to produce useful data on a single graph to make advanced planning much easier.

Table 7 presents the mission mode/flight mode combinations used in the first edition of the Handbook. The three target planets are Jupiter, Saturn and Uranus, with launch opportunities ranging from 1974 to 1986. Table 8 shows the various fixed parameters assumed in generating the payload curves. Three technology advancements are assumed available in 1980: 20 kw solar electric propulsion, shuttle-based launch systems, and space-storable retro propulsion for orbiter missions.

Figure 3 presents a typical set of payload curves for flyby-type missions: Jupiter flyby in 1977. The kink in the curves is due to the constraint in launch declination. Figure 4 presents a set of payload curves typical of orbiter missions: a 30<sup>d</sup> orbiter mission to Jupiter in 1983.

In all, the Handbook contains 80 graphs with almost 400 performance curves. Also, in a separate appendix the raw ballistic trajectory data used in generating the ballistic performance curves are summarized.

TABLE 7

MISSION SET FOR FIRST EDITION  
OF PLANETARY MISSIONS HANDBOOK

PLANET	MISSION MODES	LAUNCH YEARS	FLIGHT MODES
Jupiter	Flyby	1974-1986	Ballistic
	Orbiter	1976-1986	Ballistic
		1980,83,85	SEP
Saturn	Flyby and Orbiter	1976-1986	Ballistic
		1980,82,85	SEP
Uranus	Flyby and Oribter	1985	Ballistic and SEP

TABLE 8

FIXED PARAMETERS FOR FIRST EDITION  
OF PLANETARY MISSIONS HANDBOOK

LAUNCH VEHICLES:

1976-1986	Titan III E/Centaur Titan III E/Centaur/BII (2300) Titan III E/Centaur/TE 364-4 Titan III E/Centaur/SEP (20 kw)
1980-1986	Shuttle/Centaur Shuttle/Centaur/HE BII Shuttle/Centaur/SEP (20 kw)

LAUNCH CONDITIONS:

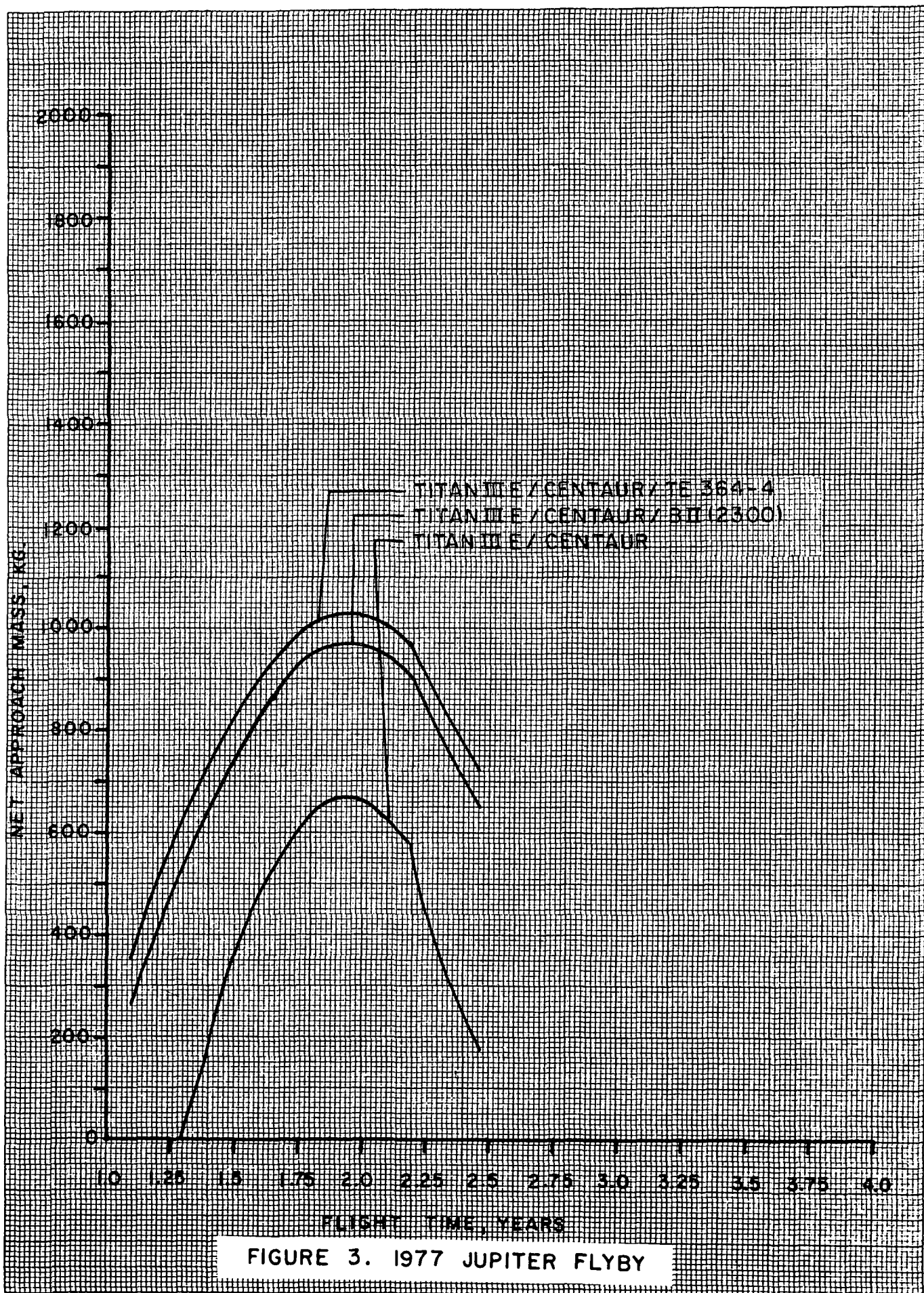
20 day window/DLA < 40° for Titan vehicles

RETRO PROPULSION SYSTEMS:

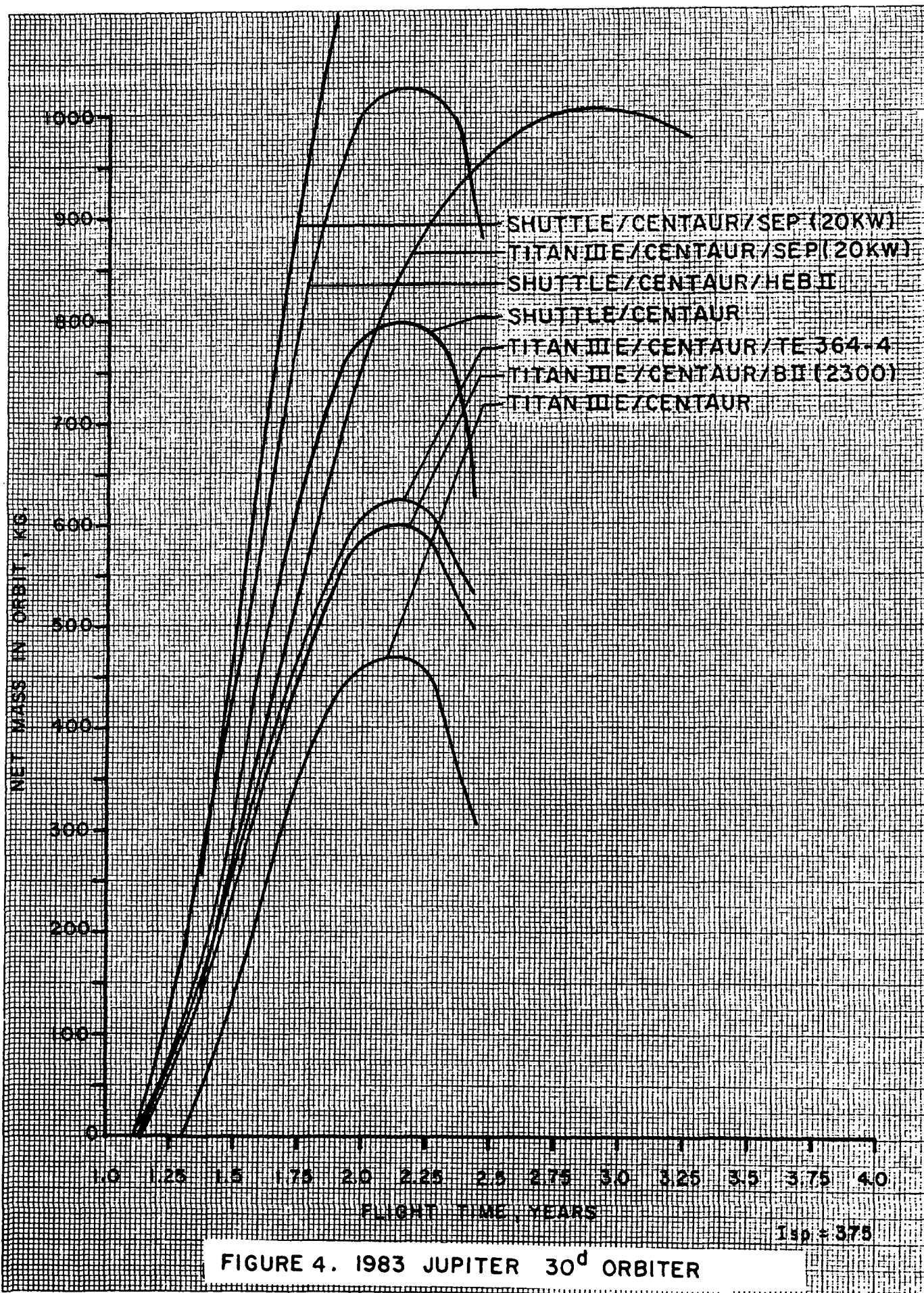
1976-1980	Earth-Storable, Isp = 285
1980-1986	Space-Storable, Isp = 375

ORBITS:

PLANET	PERIAPSE	PERIODS
Jupiter	4.0 R <sub>J</sub>	15,30,60 <sup>d</sup>
Saturn	3.0 R <sub>S</sub>	15,30,60
Uranus	1.2 R <sub>U</sub>	5,15,60









Report No. T-33  
"PLANETARY PERFORMANCE FOR ADVANCED PROPULSION  
COMPARISONS (APC) STUDY"  
by J. Niehoff and A. Friedlander  
October, 1972

Basic performance trade-offs between mission flight time and net useful payload are analyzed for advanced propulsion systems applied to unmanned planetary missions. The results are part of the much larger Advanced Propulsion Comparisons (APC) study undertaken by NASA and the AEC during 1972 and 1973. A total of 26 different propulsion options encompassing chemical rocket propulsion (CRP), nuclear rocket propulsion (NRP), solar electric propulsion (SEP), and nuclear electric propulsion (NEP) are analyzed. These options are applied to the APC Planetary Mission Model, consisting of 21 missions launched in the period 1981-1994 (Table 9). A total of almost 300 propulsion/mission combinations are analyzed. Payload versus time trade-offs are presented for each combination in tabular and graphical form. In addition, basic assumptions, stage performance graphs, and tabular trajectory data are included in the report. The results are summarized using propulsion-ready scenarios to illustrate performance conclusions. It is shown that all of the competing advanced propulsion systems, almost irregardless of technology base restrictions, provide about the same performance improvement compared to that available with only Shuttle-based Centaur and Tug stages. This conclusion applies to mission payloads increased up to 50% of baseline weights developed by JPL. It appears, based on this conclusion, that selection of advanced propulsion systems should emphasize cost and development factors, as well as geocentric mission applications perhaps, rather than basic planetary performance capability. These, and other considerations including an economics analysis, are the subject of the final report of the APC Committee.

TABLE 9  
APC PLANETARY MISSION MODEL

NO.	MISSION	LAUNCH YEAR	TARGET ORBIT SIZE	
			$R_p^b$	$R_a^b$
1	Encke Slow Flyby <sup>a</sup>	1979	-	-
2	Encke Rendezvous	1981/82	-	-
3	Venus Radar Mapper	1983	1.08 1.08	or 3.25 1.08
4	Mars Semi-Autonomous Rover	1984	1.44	10.63
5	Mercury Orbiter	1984	1.41	1.41
6	Saturn Orbiter (W/Probe)	1984-85	3.00	58.65
7	Vesta Rendezvous	1985	-	-
8	Halley Flyby	1985	-	-
9	Jupiter Orbiter	1985	4.00	45.14
10	U/N Swingby (W/U-Probe)	1986	-	-
11	Uranus Orbiter (W/Probe)	1987	1.20	36.61
12	Venus Large Lander	1989	1.08	1.08
13	Neptune Orbiter (W/Probe)	1989	1.20	41.80
14	J/P Swingby	1990	-	-
15	Ganymede Orbiter/Lander	1990	1.04	1.04
16	Mars Surface Sample Return	1990	1.30	1.30
17	Halley Rendezvous	1983	-	-
18	S/U/N Swingby (S/U-Probe)	1984	-	-
19	0.1 AU Solar Probe	1985	-	-
20	Saturn Ring Probe	1988	1.20	2.30
21	Ceres Sample Return	1993	1.10	1.10
22	Deimos Recon/Phobos Sample Return	1994	-	-

- a. Encke slow flyby not considered in performance analysis since it has a pre-shuttle IOC launch opportunity.
- b.  $R_p$  = orbit periaapse,  $R_a$  = orbit apoapse; both given in units of target radii.

## 2.4 COST ANALYSIS

Technical Memorandum No. C-10

"COST ESTIMATION FOR UNMANNED LUNAR AND PLANETARY PROGRAMS"

by J. Dunkin, P. Pekar, D. Spadoni and C. Stone

January, 1973

A basic model is presented for estimating the cost of unmanned lunar and planetary programs. The level of input parameters required by the model and its accuracy in predicting cost are consistent with pre-Phase A type mission analysis.

Cost data was collected and analyzed for eight lunar and planetary programs. Total cost was separated into the following components: labor, overhead, materials, and technical support. This study determined, with surprising consistency, that direct labor cost of unmanned lunar and planetary programs comprises 30 percent of the total program cost.

Twelve program categories were defined for modeling: six spacecraft subsystem categories (science, structure, propulsion, electrical power, communications, and guidance and control); and six support function categories (assembly and integration, test and quality assurance, launch and flight operations, ground equipment, systems analysis and engineering, and program management). An analysis, by category, showed that on a percentage basis, direct labor cost and direct labor manhours compare on a one-to-one ratio. Therefore, direct labor hours is used as the parameter for predicting cost. This has the advantage of eliminating the effect of inflation on the analysis.

Figure 5 is a flow diagram of the use of the cost model in forecasting. The boxes in the upper left involve the mission dependent information. Scaling laws, physical and mathematical relationships, and synthesis guidelines, provide the basic estimate of manhours. The remainder of the model deals with converting the basic cost element, direct labor hours, into cost.

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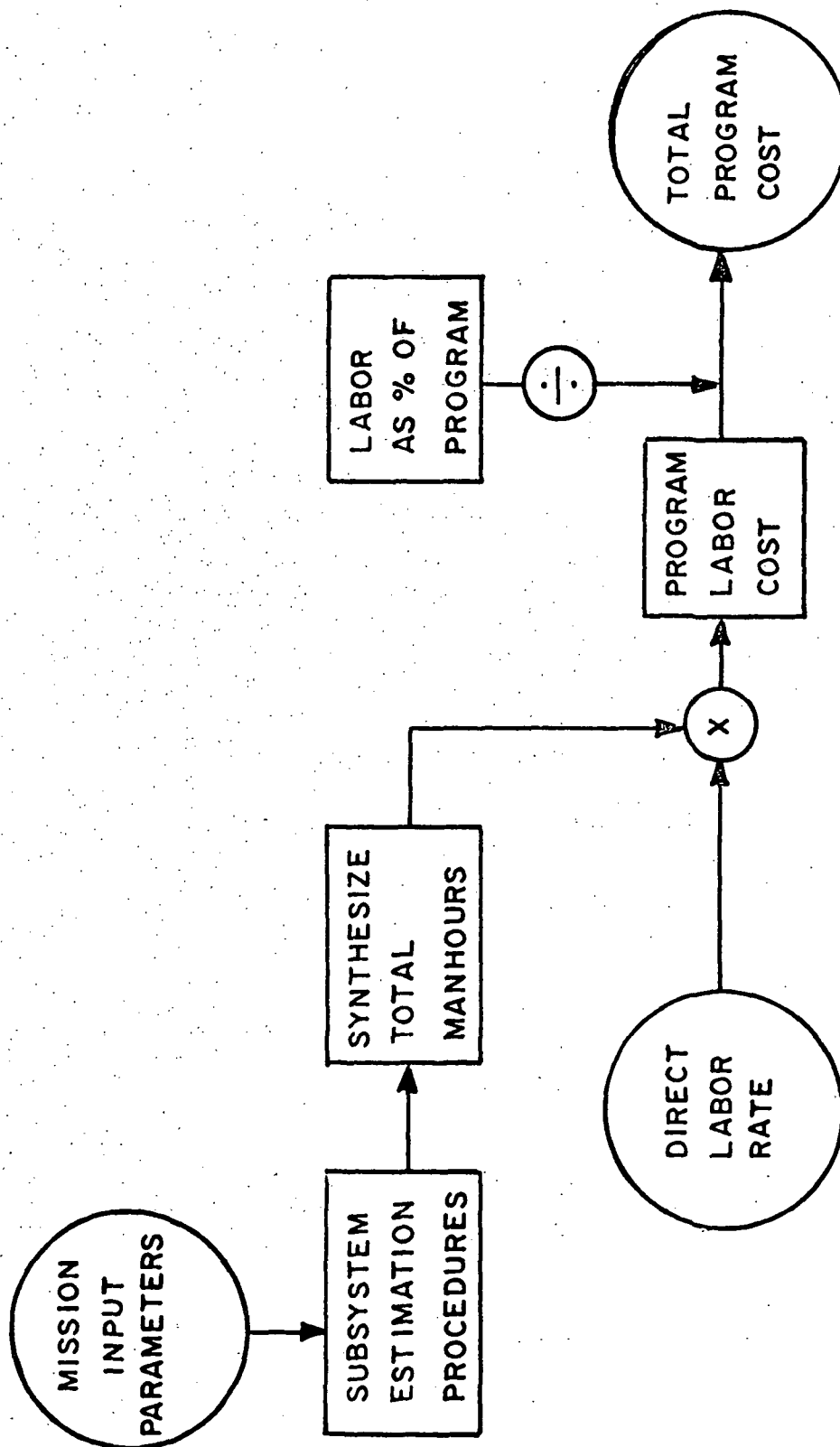


FIGURE 5.  
COST MODEL SCHEMATIC

This requires two additional steps. First, the average pay scale (\$/hr) must be determined for the period of the program. If desired, the selected pay scale could include inflation between the time of the estimate and program execution. The final step involves converting direct labor cost into total program cost. Total program cost can be determined by dividing direct labor cost by its fraction of total cost. The relationship used throughout this study is:

$$\text{Total Program Dollars} = \frac{\text{Direct Labor Hours} \times \text{Average Hourly Rate}}{.3}$$

Table 10 presents cost estimates and errors for the programs used in developing the cost model. The Surveyor program did not follow clearly established trends of the other seven programs, and was subsequently not used in the development of the model. As an example, the model was used to predict the cost of the Mariner Venus/Mercury 1973 program. The model predicted a program cost of \$120 Million, which is approximately 20 percent higher than current estimates.

Recommendations for further effort include: update the current data base by obtaining the latest Mariner 1971, Viking Orbiter and Viking Lander cost data; expand the data base by obtaining cost data for such programs as Mariner Venus 1967, Mariner Venus/Mercury 1973, and interplanetary and cis-lunar Pioneer and Explorer programs; and develop cost models for planetary atmospheric entry probes.

Table 10: Cost Model Prediction Error Analysis

Program	Actual Cost \$1000	Predicted Cost \$1000	% Error
M64	78104	62296	-20.2
M69	122052	100862	-17.4
M71	120647	150578	24.8
PIO	83858	77842	- 7.2
VO	242870	245998	1.3
VL	327924	288094	-12.2
LO	134534	164132	22.0
SU *	423195	169908	-60.0

\* not used in model derivation



### **3. SPECIAL STUDIES AND ACTIVITIES**

### 3.1 ADVANCED PLANNING ACTIVITIES

Within the Long-Range Planning Contract approximately one man year of effort is set aside for fast-response technical support to the Planetary Programs Office. In addition to real-time technical assistance, five specific minor tasks were performed in the fast-response mode during the past year as part of this effort.

The five tasks are listed below. Two of the tasks (4 and 5) were precursory studies to the Advanced Propulsion Comparisons Study (Report No. T-33, see discussion, page 35) and have been superseded by it.

1. Planetary Missions Plan, 1980-1990
2. Outer Planet Mission Options - 1975 to 1980
3. Flight time and miss distance summary data for five grand-tour type missions (J/S/P, J/U/N, S/U/N, U/N, J/P).
4. Performance Data Based on "Quick-Look" APC Analysis
5. Small Nerva (15K) Saturn/Uranus/Neptune Missions

### 3.2 NAR/SEP STAGE STUDY MISSION DATA SUPPORT

The objective of this task was to generate SEP trajectory/payload data in support of North American Rockwell's SEP Stage Study Program (MSFC Contract). The trajectory analysis ground rules, input parameters and desired results were provided by NAR with IITRI's consultation. Basically, the desired results were to show the net spacecraft mass capability for a set of nine missions as a function of such parameters as: launch vehicle, SEP power, flight time, propulsion on-time, and launch window. The parametric data will allow NAR to ascertain the capability of their stage design(s) to these mission applications, and to generate more detailed data as needed for three specific missions (Encke slow flyby, Mercury orbiter and Saturn orbiter).

Results for each mission application were sent to NAR as they were completed. The mission set is listed below:

<u>Mission Application/Launch Year</u>	<u>Baseline Power</u>
1. Encke Slow Flyby/1979	12 kw
2. Ceres Orbiter/1983	18 kw
3. S-U-N Flyby/1983	18 kw
4. U-N Flyby/1984	18 kw
5. Phobos and Deimos Rendezvous/1984	12 kw
6. Encke Rendezvous/1981	12 kw
7. Solar Probe (0.1 AU)	21 kw
8. Mercury Orbiter/1983	21 kw
9. Saturn Orbiter/1983	18 kw

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AND TECHNICAL MEMORANDA**

4. BIBLIOGRAPHY OF AS/IITRI REPORTS AND TECHNICAL MEMORANDA

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- TM-17 A Method for Determining Optimum Experiment Profiles and Resultant Data Bulk Requirements for Remote Imaging of the Lunar Surface From Polar Orbit, by P. Bock
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## 5. MAJOR COMPUTATIONAL CODES

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### Conic Section Codes

SPARC: The JPL general conic section code for ballistic and ballistic-gravity-assist flights.

NBODY (IV): The Fortran IV version of the Lewis Research Center code revised at ASC for multibody, high precision targeting and guidance analysis.

### Low Thrust Codes

BOEING CODE: CHEBYTOP I & II are fast generators of optimum low thrust interplanetary trajectories. Both solar-electric and nuclear electric powerplants can be treated. Propulsion system parameters must be specified - payload optimization can be accomplished by multiple parametric runs.

MULIMP: Uses Conjugate-Gradient search method to find minimum  $\Delta V$  trajectories consisting of up to four free fall conic arcs separated by up to five impulses. Departure is from Earth orbit and the arrival point is constrained to lie on an arbitrary conic. Velocity is matched at the arrival point (rendezvous).

### Near Planet Operations

KOFNAL: Generates ground traces of orbiting spacecraft for any number of desired revolutions. Can be used for all nine planets of the solar system. Has Calcomp capability for plotting longitude and latitude of the ground trace.

CONTUR: Generates data for Sun, Earth & Canopus occultation contours for hyperbolic flybys past any given planet.

PROFYL: A planetary encounter profile definition code.

RINGER: A code of calculating crossings of Saturn's ring plane during flyby.

AMSOCC: Generates data for Sun, Earth & Canopus occultation contours for orbiting spacecraft about any given planet.

PETARD: Similar to "KOFNAL". Generates ground traces orbiting spacecraft for any number of desired revolutions for any of the nine planets of the solar system. Has Calcomp capability for plotting latitude or altitude as a function of time from periapse on semi-log plots.

CAPTR: Set of two codes developed to perform orbit and landing maneuvers about a natural planetary satellite.

ETY 1: Solves differential equations describing motion of a spacecraft entering the atmosphere of a rotating planet with a spherical gravity field. Present version assumes fixed values of the drag coefficient and lift to drag ratio. Atmospheric density is computed as an exponential function of altitude.

STAGE/BURN: Calculates injection energy ( $C_3$ ) requirements for a specified payload from an Earth parking orbit. Uses a fast, accurate analytical approximation to finite thrust injection maneuver. Program is set up to handle multi-stage (up to 4 stages) injection vehicle. Both chemical and nuclear rocket stages can be used.

APPROACH: Solves the targeting problem for planetary entry probes ejected from fly-by spacecraft. Computes deflection increment, entry conditions and sensitivities, as well as post entry probe to spacecraft range and communication angle.

### Guidance and Orbit Determination

GNAP: JPL low thrust navigation code.

COMODE: High precision comet orbit determination code, taking into consideration gravitational effects of Sun and all nine planets simultaneously.

ORBOBS: A Fortran IV program for determining minimum separation intercepts of a Jupiter orbiter with the four Galilean Satellites; Io, Europa, Ganymede, and Callisto.

SURVEY: Generates sighting conditions for comets over a specified length of time. Has Calcomp capability for plotting sighting conditions as function of time from perihelion.

### Specialized Codes

PLANET \* PLANET: JPL planet ephemeris subroutine package.

PLASAT: JPL ephemeris subroutines for planetary natural satellites.

ASTDAT \* 1971: JPL asteroid and comet ephemeris data tape.

MIMIC: A Fortran IV-like system for simulating, on the 1108, an analog computer and thereby easily doing integrations.

BMD: A general statistical analysis package from UCLA used for multiple regression analysis of cost data.

### Hewlett-Packard 9100 Calculator System

The following is a partial list of programs developed by Astro Sciences for use on the HP system:

CT: Transforms coordinates of approach trajectory from ecliptic to equatorial for any given planet.

P3: Determines flyby or orbiter payloads for a given launch vehicle, chemical retro system (if any), and trajectory energy requirements. Plots payload versus flight time.

3DV: Determines  $\Delta V$  requirements for orbiting a natural satellite. Uses a derivative of the bi-elliptic transfer.

SRO: Calculates occultation parameters of a spacecraft being occulted by the rings of Saturn. Can handle either a flyby or orbiter of Saturn.

MR2: Multiple linear regression of the form  $Z = A_0 + A_1X + A_2Y$ .